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RESEARCH IN ELECTRONIC/ELECTRICAL ENGINEERING AT BRITISH UNIVERSITIES

IRVING KAUFMAN

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This is a summary report of research found in electronic/electrical engineering at British universities during the author's tour of duty as liaison scientist with the London Branch Office of the US Office of Naval Research, August 1978 to August 1980. The first section lists the agencies funding research in the UK, with some figures on the amount of funding and its distribution. This is followed by a brief discourse on British universities, with facts relevant to the student population in EEE at universities, and a comparison of British and American graduate and undergraduate

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programs. Some special arrangements in relation to research are treated next, followed by a general assessment of graduate research at British universities. The final section contains, in summary form, information about the research found by the writer during his visits to 22 universities in England, Wales, and Scotland.

TABLE OF CONTENTS

RESEARCH IN ELECTRONIC/ELECTRICAL ENGINEERING AT BRITISH UNIVERSITIES

This is a summary report of research found in electronic/electrical engineering (EEE) at British universities during the author's tour of duty as liaison scientist with the London Branch Office of the US Office of Naval Research, August 1978-August 1980. The first section lists the agencies funding research in the UK, with some figures on the amount of funding and its distribution. This is followed by a brief discourse on British universities, including facts relevant to the student population in EEE at a university, and a comparison of British and American undergraduate and graduate programs. Some special arrangements relevant to research are treated next, followed by a general assessment of graduate research at British universities.

The final section presents, in summary form, information on the research found by the writer during his visits to 22 universities in England, Wales, and Scotland.

I. Research Support in the United Kingdom

The organization of science and the financial support structure in Britain is extremely complex, possibly because of the long history of the United Kingdom's involvement with science and technology. While a basic method of grouping scientific establishments is by reference to their sources of funding, in the case of many organizations this system fails to operate. This is because some "state-aided" institutes, for example, are, in fact, entirely reliant on government funds, while some government-funded establishments still have an investment income (from their days of private ownership) on which they draw without reference to the government.

A detailed chart of all the sources and amounts of research funding would require a major undertaking—of quite a different nature than has been the mission of this writer as liaison scientist. However, a fairly good idea of the sources of research funding can be obtained by a flow chart that demonstrates how the government disburses its financial resources. This is seen in Fig.1, (a),(b), and (c), which are taken from an organization chart entitled "A nature guide to how Britain runs its science, 1977-78." (This is the latest edition that was available to the writer.)

Funding for research in the field of electronics/electrical engineering can originate in any of the departments or ministries listed in the boxes at the bottom of Fig. 1(a). Since there is a great deal of research in progress in British universities, we first examine funding through the Department of Education and Science. This is followed by some remarks relating to other departments or ministries also funding research.

1. Department of Education and Science

As indicated in Fig. 1(b), the Department of Education and Science disburses funds through three different organizations. Of these, the University Grants Committee has the basic function of operating the British universities. The concern here is funding of the educational aspects, such as providing salaries for professors and other teaching personnel, the purchase of laboratory equipment for instruction, etc. Research, on the other hand, is supported principally by the Research Councils. For the fields that I covered, i.e., electronics/electrical engineering, and in particular device research, the relevant authority here is the Science Research Council (SRC).

It was of interest to me that funding by SRC in the academic institutions that I visited is not generally used to pay salaries of academic investigators. The latter receive their salaries from their universities, with the understanding that university academic personnel are expected to do research, with the teaching load generally adjusted to make this possible. The idea of "released time," (time "released from teaching") to be paid out of a grant fund, which is found in many American universities, appears not to exist in British universities.

SRC, founded in 1965, is responsible for all fundamental science (including engineering science), with the exception of that which falls within the jurisdiction of the other research councils.

For 1976-77, i.e., the year ending 31 March 1977, SRC received a parliamentary grant-in-aid of £125,134,000 made up as follows:

Science Research Council, undesignated	£94,289,000
For European Organization for Nuclear Research, subscription	23,160,000
For NATO scientific schemes	847,000
For European Space Agency subscription	6,838,000

Another £2½M were received from such miscellaneous sources as contributions from NATO for NATO postgraduate awards, etc.

In 1976-77, SRC awarded 1,614 research grants, totalling £28.7M. Funding of successful applications was at the rate of approximately 42% of the funds sought.

The distribution of the £127.7M was as follows:

Research grants

Engineering	8%
Science	8%
Nuclear physics	2%
Astronomy, space, radio	3%

Postgraduate training awards

Science, nuclear physics, astronomy, space & radio	7%
Engineering	4%

Intramural Expenditure in Support of University Research

Rutherford Laboratory	13%
Daresbury Laboratory (Nuclear Physics)	8%
Observatories	3%
Appleton Laboratory (Radio Production)	9%
Central Facilities	2%
Administration	3%

International Payments

Euro. Organ. for Nuclear Research (CERN)	19%
Euro. Space Agency (ESA)	5%
Institut Laue-Langevin, Grenoble	4%
Others	2%

As shown in the organization chart of Fig. 1(c), SRC is advised by four boards. These, in turn, have a number of specialized committees and are responsible for certain facilities. Electronics/electrical engineering research is in the domain of at least two of these boards. The Engineering Board supports aeronautical and civil engineering, control engineering, metallurgy and metals research, computing science, and polymer science. The appropriate committee here is the Electrical and Systems Engineering Committee. The Science Board, among others, supports research in physics, with the relevant committee of this board appropriately called the Physics Committee.

2. Ministry of Defence

As is well known, a considerable amount of R&D in electronics is being supported by the Ministry of Defense (MOD). Some outstanding work in electronics, for example, has originated at the Royal Signals and Radar Establishment. Finding out about details of MOD funding for R&D, however, is another story. Before I left London, one of my colleagues told me that he had recently requested from the Ministry of Defence a comprehensive list of contracts and grants supported by this Ministry, but he found that no such list is being published at this time.

3. Department of Industry

Although research support by the Department of Industry is significantly less for electronics/electrical engineering than that from SRC, it is by no means insignificant. No current figures were available during preparation of this report, but the reader can get an idea from support levels during 1972-73. In that year, support for electronics was £1.1 million; R&D support for computer science and automation was £12.8, out of a total budget of £57.7. (To aid in comparison, the funds for undesignated use by SRC for 1976-77 were nearly twice those for 1972-73.) An interesting aspect of the Department of Industry is that this department operates five industrial research establishments. These are: (a) The National Physical Laboratory, which acts as a National Standards Laboratory; (b) The National Engineering Laboratory, which provides a wide range of services, including testing for the engineering industry (In Britain, the term "engineering industry" usually means manufacture of mechanical machinery such as automobiles, locomotives, etc.); (c) The Warren Springs Laboratory, which performs research on bulk handling of products, mineral processing, design and implementation of process automation schemes; (d) The Computer-Aided Design Centre, which provides specialized computing facilities and sponsors the application of computer-aided design techniques; (e) The Laboratory of the Government Chemist, which provides analytical services to government departments and performs research in food chemistry, pesticide residues, and environmental pollution.

4. Department of Energy

The Department of Energy is responsible for the oil industry, the gas industry, international discussions on energy policy production, the electricity, coal, and atomic energy industries, and research and development work relating to energy sources.

5. Other Departments

Although it is quite probable that some research in Electronics/ Electrical Engineering is sponsored by some of the other governmental departments, the amounts are small when compared to that supported by SRC.

II. Electronics/Electrical Engineering at Some Universities in the United Kingdom

Although Americans frequently refer to Britain as "England," the United Kingdom is actually composed of what in Britain is often considered as four different countries: England, Wales, Scotland, and Northern Ireland Since the population of England (46 million) is nearly five times that of the other three combined, one might assume that the English method of organizing education is universal throughout the UK. Actually, that is not quite the case, although there are strong similarities.

1. Universities in England and Wales

According to *Guide to World Science, Vol. 1, United Kingdom and Republic of Ireland* (A.P. Harvey, Editor; Francis Hodgsons, Publisher, Guernsey, Channel Islands, 1974) there are 34 universities in England and Wales. The oldest of these are Oxford, Cambridge, Durham, and Wales. The latter is a federal university of seven separate insititutions. Most of the other universities were established in the latter part of the nineteenth century (e.g., Manchester, Liverpool, Leeds, Sheffield), while a large number of the universities are much newer. During my tenure at ONR London I visited Departments of Electronic and/or Electrical Engineering of a number of these universities. A later section of this report contains summaries of these visits, emphasizing, in particular, the research in progress.

The universities are autonomous bodies and have complete academic freedom. Their rights and functions are exercised in most cases by royal charter. However, even though they are autonomous, nearly all their funding comes from the state. There are variations, of course, for the older universities that have been endowed financially over the centuries have considerable resources to draw on in addition to the state funding. But when it comes to research funding, the writer has heard the same story at Oxford that he has heard at some of the new institutions; "We will be able to carry out this research provided we are funded by the Science Research Council."

As stated earlier, academics at universities are expected to perform research along with their teaching. That was not necessarily the intention when the state established another group of institutions of higher education in the 1960s—the polytechnics. These institutions were designed to be teaching establishments. However, as it has turned out, some of the research in progress at the polytechnics is of as high a quality as that in many universities. This makes the polytechnics at this time somewhat of a dilemma in the educational system. This theme is expanded on in some recent articles in *European Scientific Notes* (See *ESN* 32-6:203 [1978]; 33-5:195 [1979]).

The fact that there are so many institutions of learning has, to the observation of the writer, caused an interesting distribution of the student population to occur. But to explain this requires a digression into the educational procedure.

(a) The General Certificate of Education

In the US, a common way of judging a student's expected performance in college is the high school grade record, based on the grades received in various courses. Moreover, a student is generally expected to graduate from a high school prior to entering a university. It is well known, however, that high school standards may differ considerably, so that there is no uniform gauge that can be applied reliably by examination of a student's grades. This is why university admissions boards now also pay close attention to results of such tests as the SAT (Stanford Achievement Test), and the individual's references.

In Britain, university admission is said to be based completely on performance in publicly administered examinations. In England and Wales such examinations are called the General Certificate of Education (GCE).

The GCE is administered by some 9 examining bodies, mainly associated with the universities in England and Wales. There are basically two sets of examinations, the Ordinary and Advanced, known as "O and A levels." O levels are normally taken after 4 or 5 years of secondary school; A levels after 6 or 7 years.

Admission to a professional school, such as one that trains nurses, for example, or qualifications for a job such as clerk in the Civil Service generally requires a "pass" in O levels in a specified number of subjects. Advertisements for jobs thus may state that the basic requirement for acceptance for an application is a "pass" in three O levels. The idea of a high school diploma within the British framework is therefore of no meaning.

Admission to a university requires a "pass" in a number of O levels, with the specific number determined by the particular university, but 4 subjects is a common number. In addition, a "pass" in several A levels is required.

Suppose a young man wishes to enter a university to study electrical engineering, and he wants to get into as good a university as possible. What must he do?

First of all, he must pass the requisite number of O levels. Generally he does this at age 16. For all practical purposes, from there on the formal portion of training in cultural subjects such as art or history is finished. For the next 2 years he must concentrate on technical subjects, principally mathematics and physics. He then takes his A levels. Here it is important that he do as well as possible, for A levels are graded from A through E.

He then applies to the various universities of his choice. Upon receipt of his application, the universities examine his performance in the A levels. The more established universities in his chosen field may have a basic requirement that in order to be considered, a student's grades in A levels must be a minimum of two Bs and one C. If a student has applied to a university that has this requirement and qualifies, he is in a good position to be considered for the limited number of openings for the first year program at that university. If his A level performance was poorer, then he must settle for a university with less stringent requirements.

A problem in judging the student's qualifications clearly arises if that student did not pass through the system of British secondary schools. A few foreign high schools such as, perhaps, several in India are now known to have very high standards, so that outstanding students from such schools can be depended on to be good students in Britain. Even the most selective of universities would therefore accept such foreign students. The standards of schools from many other countries, on the other hand, are not known, and as a result students applying from these may find it difficult to be accepted at the university, so they apply to one of the polytechnics. As a result, some of the polytechnics have more foreign than British students. This was the case in the Electrical Engineering Department of the one polytechnic that I visited—the Polytechnic of Central London.

The undergraduate program in electrical engineering in British universities is a 3-year program. This is felt adequate because of the intense training the student receives in mathematics and physics prior to entering the university, i.e., in the preparation of A levels. To provide the budding engineer with some practical training, it is common practice to require that a portion of the 3rd year be devoted to what can be called a "final year project." As a result, it is frequently thought that students graduating in electrical engineering from an English or Welsh university have reached an educational level equivalent to somewhere between a bachelor's and a master's degree in the US, and this could well be a correct assessment.

(b) Graduate Training

While in most well-established British universities only a minority of electrical engineering undergraduates are not British, this is not the case in graduate work. The probable reason is that British industry has not yet recognized the value of a PhD in Electrical Engineering. A student with a PhD who enters industry after 3 years of research following his bachelor's degree may well find that he is being paid a lower salary than the person who entered industry 3 years earlier, immediately after the bachelor's degree. (Incidentally, the PhD work is chiefly research. There is not the exposure to the many courses that we require of PhD candidates in most American universities.)

Because such a large percentage of graduate students in electrical engineering are foreigners, one finds much of the graduate research being conducted by these foreign students. In view of this situation, it was feared, at the time of my departure from Britain (August 1980), that a new policy of government at Westminster which required foreign students to pay considerably larger fees than paid by British students would reduce the amount of research carried out in universities. The new policy was to go into effect in the fall of 1980.

One of the universities that it was thought would be affected severely by this change was UMIST (the University of Manchester Institute of Science and Technology). I visited UMIST some time ago and found the Electrical Engineering Department to be very active in applied research.

It is recommended that another visit by ONRL be planned about two years after the new government policy has been in effect, to see if a change indeed occurred.

2. Scotland

Scotland has a slightly different system than England and Wales. Instead of a GCE, Scotland holds its examinations for the Scottish Certificate of Education. Again, there are two sets of examinations, "ordinary" and "higher," but the "higher" is apparently of a lower level than the A levels of England and Wales. Undergraduate electrical engineering education in Scotland is a 4-year program. Accordingly, few Scottish students take undergraduate training in English or Welsh universities. This is not true at the graduate level however. Nor is it true for faculty.

3. Northern Ireland

Regrettably, I did not visit Northern Ireland, the "overseas" part of the UK, and therefore have no first-hand impressions or information.

4. Some Special Programs at British Universities

During my visits to a number of British universities I learned of several special projects that may be of interest to the reader. the list of these projects given below is not to be considered as all-inclusive. There are probably a number of other projects in electrical engineering/electronics that should be mentioned but that I was not told about.

a) Semiconductor Technology—Integrated Circuits

In response to the need for trained semiconductor specialists and for applied research in that field, the SRC decided some time ago to have some specific institutions become the UK experts in one phase or another of semiconductor technology. According to Dr. J.M. Robertson, director of the Central Microcircuit Processing Facility of the University of Edinburgh, the institutions chosen, their specialities, and the grants made to them at the time of my visit to Edinburgh (Nov. 1979) were:

University of Edinburgh: Silicon MOS	£600,000
University of Southhampton: Silicon MOS and Bipolars	£400,000
Rutherford Laboratories (an establishment of SRC): Electron Beam Lithography	£1,000,000
University of Surrey: Ion Implantation	£100,000
University of Sheffield: III-V Compound Semiconductors	£300,000

These institutions were to perform their own work in their respective specialties as well as to serve other elements of the British system. For example, the Edinburgh Central Microelectronics Processing

Facility was to make integrated circuits (ICs) for in-house research work, for research projects in other universities throughout the UK, and also for research requirements generated in industry. I was somewhat surprised (and pleased) to find that the cooperative efforts actually extended somewhat farther. For example, when I visited Prof. J.O. Scanlon of University College Dublin, I learned that the design and fabrication cf new electrical filters originated by Scanlon and his group were being carried out by the University of Edinburgh.

At the time of my visit to Edinburgh the new laboratories were still not operational. Robertson, nevertheless gave me a breakdown of how SRC money was being spent in the establishment of his facility, as follows:

Equipment Costs:	
Base level equipment	£ 80,000
Additional equipment, including polysilicon reactor, Cobalt mask aligner, HP system for measurement of resistivity and threshold voltage	£100,000
Ion implanter (Lintott, 200keV @ 4 ma; 600 keV @ 1.45 μa)	£233,000
Base annual salaries	£50,000
Annual cost of consumables	£20,000 to £30,000

In addition, the cost for building modifications was £100,000 and the installation of the air conditioning and laminar flow was £450,000. Some of this money obviously must have come from the university. The total laboratory space at Edinburgh for this facility was 4,000 sq. ft.

Robertson stated that he expected SRC to continue to support this facility indefinitely in 4-year cycles, with evaluation every 2 years.

At the time of my visit to Sheffield (late 1978), the III-V facility was not yet operational. According to more recent reports from Prof. P.N. Robson, its director, the SRC central facility was completed in 1979, the III-V layer growth by liquid phase epitaxy had started, and special GaAs devices were being grown for the Universities of Cambridge and Liverpool.

The concept of central facilities is a very good one, for there are many times when a specimen of a certain structure or composition is needed by a researcher who is not able to fabricate such a component himself. However, the selection of a facilities director must be approached with caution. One reason for this is that if the director himself wants to be an active researcher and finds that his time is taken up in having to service other, possibly competing university groups, he may easily begin to resent it. It will be of interest to see how Robson, who has been an active researcher, feels about his facilities and activities two years from now.

b) Wolfson Foundation Units

In the US, and certainly within my own personal experience there has long been great concern that a state university should not compete with private enterprise. The UK appears to have a somewhat different point of view; I found several universities that have special units engaged in development, testing and even manufacturing that normally would be carried out in industrial laboratories. In a number of cases these activities were carried out by organizations that had the name Wolfson attached to them.

The Wolfson Foundation (251 Tottenham Court Road, London W1P OAE) was founded in 1955 by Sir Isaac Wolfson for the support of scientific and medical research in higher education. The foundation awards grants towards the construction of new education buildings and for the support of projects in the fields of applied science, commerce, and education which in the judgment of the trustees are most likely to improve the economic position of Britain and help the modernization of British industry. It is said that the promotion of scientific research and the encouragement of graduate studies in Britain are among the foremost concerns of the trustees. There is now a Wolfson College at Oxford University and another one at Cambridge. Institutes created by the Wolfson Foundation that I have had contact with are:

i) Wolfson Microelectronics Institute of the University of Edinburgh

Established in 1969 with a grant of £130,700, this institute is now a self-funded research and development organization covering microelectronics design, instrumentation and systems development, with an expanding emphasis on microprocessors. Its annual turnover for 1979 was £200,000. In addition to its current director, Dr. A.D. Milne, there are 16 engineers and 4 technicians. Recent work has included the development of a digital micrometer, contract work for a telecommunications firm in Denmark, and custom design, fabrication, and defect analysis for a number of communication and semiconductor companies.

The great advantage of locating this institute within the university is that faculty persons who have been heavily involved in research related to development projects of the institute (e.g., acoustic surface waves, signal processing) act as consultants and because of their proximity are virtually immediately available.

ii) University of Southampton--Faculty of Engineering and Applied Sciences

There are five Wolfson units associated with the Faculty of Engineering and Applied Sciences at Southampton. They are: (1) Wolfson Unit for Noise and Vibration Control; (2) Wolfson Marinecraft Unit; (3) Wolfson Applied Electrostatics Advisory Unit; (4) Wolfson Industrial Unit (allied with the Department of Electronics and functioning in the fields of lasers, fiber communications, opto-electronics, digital and analog computers, instrumentations, and integrated circuits); (5) Wolfson Materials Advisory Service.

Although I did not visit Southampton, I met and conversed with Dr. J.A. Cross, manager of the Applied Electrostatics Unit. The mission of the unit is to consult on problems of electrostatics, including useful applications and hazards. According to Dr. Cross, the unit makes use of a wide range of instrumentation, including electric field measurement equipment and diagnostic techniques applied to charged particles.

iii) <u>University College Cardiff (of the Univ. of Wales)</u>

The Wolfson Centre for Magnetic Technology at Cardiff enjoys an international reputation and is the SRC Centre of Excellence for Applied Magnetics Research. The principal individuals involved are Prof. J.E. Thompson, and Drs. A.J. Moses, A.J. Collins, A. Bazac, and K.J. Overshot (deputy director). Projects in the centre extend over the whole spectrum of magnetics, including magnetic recording, thin film technology, electrical sheet steel, transformers, magnetic devices and permanent magnets. The unit has had contracts totaling over £1.25M since its initiation 14 years ago.

iv) <u>The University of Aston in Birmingham</u>

Tied closely to the George Alexander Laboratories of the University of Aston in Birmingham, in the Department of Product Engineering, is the Wolfson Industrial Material Forming Unit (WIMFU), under the leadership of Prof. D.H. Sansone. The work is on metal deformation and research, directed towards the needs of industry. Inventions arising are usually patented with the industrial firm that supports the research or with the National Research and Development Corporation.

This research covers the broad areas of rolling and drawing of metal, with special emphasis on ultrasonics for drawing metal tubes, cups, and wires. Support for the laboratory is approximately equally obtained from industry and government departments. The university covers the overhead costs.

A recognized function of WIMF is to transfer ultrasonic material forming technology to industry, by fabricating and selling the equipment that has been developed to industry.

(c) <u>Additional Industrial Ventures at Universities</u>

In addition to the Wolfson units there are a number of other industrial ventures at British universities. For example, I attended a meeting at which N.J. Phillips of Loughborough University of Technology discussed his work on holography. During a conversation with D. Croucher, the London representative of the Belgian company Agfa-Gevert, Croucher told me that his company views Phillips' operation as Agfa-Gevaert's holographic research laboratory.

Even more of an industrial venture is Industrial Development Bangor (UCNW) Ltd. As the initials in the name imply, this organization is closely associated with University College of North Wales, located in Bangor. This organization manufactures and markets specialized electrical and electronic equipment. Examples are test equipment for electrostatics investigations, a profilometer (under license from British Steel Corp.), high-voltage supplies, and a myometer developed at Hammersmith Hospital, London.

5. Graduate Reserach in Some British Universities—Impressions

During my tenure of two years at ONR London I visited a number of British universities, though by no means all of them. In most cases my visit was to the departments of electrical or electronic engineering. In a few instances I also talked with individuals from applied physics. While my principal interests were in research on electronic devices, in many cases I received information on much other work also in progress.

My principal impressions were:

1) There is a lot of good and interesting research and development in electrical and electronic engineering departments in progress in British universities. Much of it is quite sophisticated and highly specialized, of course. A few of the topics that came to my attention seemed novel, and sometimes spectacular. Examples are: (a) The nuclear magnetic resonance imaging of bodily cross sections by Prof. P. Mansfield and colleagues (Univ. of Nottingham) and Prof. J. Mallard and others (Univ. of Aberdeen); (b) the work on the use of Langmuir-Blodgett films to fabricate electronic devices, by Prof. G. Roberts and colleagues (Univ. of Durham), and Dr. M. Taylor (Univ. College of North Wales); (c) the antenna/signal processing techniques of A.P. Anderson and his group (Sheffield); (d) the noise radar of Prof. A.L. Cullen (Univ. College London); and (e) the spectacular holograms of N.J. Phillips (Loughborough Univ. of Technology).

2) In Britain it is expected that faculty personnel engage in research along with their teaching duties, and time seems to be made available for this. This means that the problem of faculty "release time" of American universities, in which permanent faculty must find funds from a grant or contract to pay for the portion of their working time in which they are engaged in research, does not exist. It may therefore be easier, on the average, for faculty to perform research in British universities than in the US.

3) Faculties may well have more time for research than some of their US counterparts because the undergraduate program is only 3 years, there is limited enrollment, and relatively few graduate courses are being taught in Britain. While some universities offer MS programs that involve some classwork, to obtain a PhD usually involves only research—no courses, and no qualifying exams.

4) Research funds are obtainable from SRC. For 1978-79, SRC made 2,242

grant awards, for a total funding of £58.04M. The number of grants awarded was 50.8% of those for which applications were received; the funds awarded were 40.6% of those requested. Several individuals who have worked in both US and British systems have told me that there is much less proposal writing required in Britain than in the US.

5) As in the US, those universities that have an unusually large amount of research and development in progress are normally busy selling their talents, to SRC, to the military, and to private industry.

6) A listing of research projects that was helpful to me is given in several volumes entitled *Research in British Universities, Polytechnics and Colleges*, published by R.B.U.T.C. Office, the British Library, Boston Spa, Wetherby, West Yorkshire LS23 7BQ. Vol. 1 is for Physical Sciences; Vol. 2 for Biological Sciences; Vol. 3 for Social Sciences.

III. Visits to Some British Universities

This section presents, in summary form, information obtained from visits to a number of British universities. In some cases, more detailed information has already been published in *European Scientific Notes (ESN)*. In other cases, there was insufficient time to prepare detailed write-ups prior to my leaving ONR London. Any reader desiring more information is invited to contact me at Arizona State University, Tempe, AZ 85282; telephone (602) 965-3424.

A. ENGLAND

1. Cambridge University

Visit only to Electron Beam Systems Group, particularly to Dr. H. Ahmed and his principal assistant, Dr. G.A.C. Jones: sophisticated and extensive work in electron beam lithography and electron beam annealing. This small group has been a world leader in scanning electron microscopy techniques. Support from SRC; Ministry of Defence; industry. Other work: (1) Dr. W.C. Nixon, electron microscopy and microelectronics inspection; design, construction, operation of 600 keV, 2Å-resolution electron microscope. (2) Dr. K. Smith: computer processing of electron images; problems of field emission and electron lenses.

2. University of Durham

Visit to Department of Applied Physics and Electronics, headed by Prof. G.G. Roberts. Dr. Cyril Hilsum, FRS, of Royal Signal and Radar Establishement (RSRE), Great Malvern, is on staff as visiting professor.

Extensive thin-film work based on Langmuir-Blodgett dipping technique. They have fabricated InP FETs by this method and were working on extending the technique to constructing photovoltaics, electroluminescent films, and Chem FET structures during my visit (Nov. 1979).

Dr. J. Woods investigates photoelectronic properties of II-VIs. (Electroluminescence of ZnSe and ZnS Schottky barrier devices, MIS structures on ZnSe; potential barrier of $CdS-Cu_2S$ solar cells.) Also: photoelectronic and photochromic properties of rutile. (Single crystal rutile grown in plasma fusion process in conjunction with Trioxide International Ltd.)

Dr. J.S. Thorp uses spin resonance, coupled with X-ray and optical methods, to study refractory oxides, nitrides, and ceramics. Examples: Si_3N_4 (for turbine blades and semiconductor surfaces), MgO doped with transition ions, TiO_2 (Problem: Why does white paint turn yellow after some time?).

General impression: Roberts is pulling his department into prominence with scientific work of industrial interest.

3. University of Leeds

Visit to Department of Electrical and Electronic Engineering (in late 1978). Head of Department: Prof. P.J. Lawrenson. His work: electrical machines, control, e.m. field problems—principally in machines. Emphasis on superconducting machine research (with £150,000 support), but without actual superconducting experiments. Specific problems: screening of magnetic fields, electromechanical stability; control motors, vehicle transmission systems. Lawrenson said that he has designed stepping motors that "frankly, no one else had been able to design."

Prof. P.A. Matthews: microwave communication, radio propagation, microwave thermography, signal processing. Principal work: applying communication techniques such as spread-spectrum signalling.

Prof. J.D. Rhodes (special professorial chair): very impressive, young/middle age. Principal work: electrical filters, mainly for microwaves; does a lot of consulting; has his own firm to fabricate his designs; claimed to have achieved temperature-invariant pulse compression using surface acoustic waves.

D.V. Morgan and M.J. Howes: very active researchers in semiconductor devices and their interaction with circuits; also emphasis on semiconductor contacts.

Altogether: Four professors, 14 senior lecturers or lecturers. Department seemed quite mature, with research on variety of topics.

4. London University (also called The University of London)

London University has a number of colleges that operate virtually as independent universities. Only Imperial College of Science and Technology, Kings's College, Queen Mary College, and University College have departments of electrical engineering.

(a) Chelsea College: Prof. A.K. Jonscher, Chelsea Dielectrics Group, Dept. of Physics (Brief visit in August 1979).

During the last several years Jonscher has been the proponent of a law of "Universal Dielectric Response" which states that below 10GHz the ratio $\chi''(\omega)/\chi'(\omega)$ for almost all solid dielectrics is a constant— in contrast to Debye behavior, for which this ratio is $\omega\tau$. There have been theoretical collaborations for his investigations relating to this law with K.L. Ngai and C.T. White of the Naval Research Laboratory, Washington, DC. A number of related experimental investigations, for frequencies down to 10^{-5}Hz, were in progress. Work planned for the future was to deal with the structure of biological systems by themselves and in solvents, deep levels in semiconductors, electrical breakdown, interaction between charge carriers and the lattice, relation of the "universal dielectric response" and 1/f noise, dispersive transport, and fast ion conduction.

(b) Imperial College of Science and Technology: Prof. J.C. Anderson, Electrical Engineering, brief visit in January 1979.

Anderson's group, with the mission to perform work in "device-oriented solid state physics," had six members of staff, four postdocs, and 21 PhD students. Work in areas of thin-film transistors (TFTs), Chem FETs (Dr. Juhasz), and in solid state photochromics, amorphous semiconductors, photolysis of solids, and surface effects in semiconductors (Dr. Mino Green).

Anderson claimed that his group could fabricate TFTs with characteristics as good as silicon devices but refused to give details.

I was impressed with Green, who had been director of Zenith Radio's European research effort. His most recent work, with transition metal oxides (M_xWO_3 in particular) could result in solid state displays competitive with liquid crystals.

(c) Queen Mary College

Details of a visit to Prof. P.J.B. Clarricoats, Dr. A.D. Olver, and Dr. E.H. Mamdani were reported in *ESN* 34-2:59 (1980). The principal work dealt with antennas and with fuzzy sets.

(d) University College London (UCL)

Details of a visit to the Electronic and Electrical Engineering Department of UCL by D.K. Cheng of ONRL were reported in *ESN* 30-7 (1976). The three research groups in this outstanding department are the Electromagnetics Group (EMG, headed by Prof. A.L. Cullen, FRS), the Physical Electronics Group (PEG, headed by Prof. E.A. Ash, FRS), and the Systems Group (SG, headed by Prof. D.E.N. Davies).

In EMG, work on active antenna arrays, microwave measurements, and em theory described by D.K. Cheng has continued. A newer project deals with a solid state microwave noise radar which, basically, should be free from interference. By up-conversion of lower frequency noise to 8GHz, with received signal conversion to IF frequencies and delay and correlation with the transmitted noise in a digital correlator, ranges up to 1 km had been achieved at the time of my visit to UCL (Sept. 1978).

The activities of PEG have continued to be numerous: acoustic imaging, signal processing, and nondestructive testing; thin film materials research, including diffusion, ion exchange, and molecular beam epitaxial methods; integrated optics, including the application of integrated techniques to the control of optical signals in multimode fibers, deposition of Langmuir-Blodgett films for optical waveguide applications. A more recent subject of Ash: photothermal microscopy.

In SG, work has continued on such systems-oriented problems as antenna null steering, multipath and scintillation fading at 36 GHz and 110 GHz, measurement of thermal plumes in the atmosphere by acoustic radar sounding, and optical fiber communication systems.

5. University of Manchester

My visit to the University of Manchester and the research observed there were described in *ESN* 34-6:276 (1980).

6. University of Manchester Institute of Science and Technology (UMIST)

Activities at UMIST were described with those at the University of Manchester in *ESN* 34-6:276 (1980).

7. University of Newcastle upon Tyne

Electrical engineering at this university had come to my attention before my arrival at ONRL through publications of Prof. H.L. Hartnagel, who had built up a very active semiconductor technology group. Since Hartnagel had left in October 1978 to take up a professorship in Germany, Newcastle was in a transition period during my visit in July 1979.

There were 12 staff members. Prof. D. J. Kinnimeth was starting work on computer aids to the design of VLSI circuits. Prof. M.R. Harris was starting work on stepping motors. Others: Prof. A. Holt: digital filters, application of microprocessors; Dr. J. Brown: motors; J. Dinely and Dr. Harrington: power systems; Dr. W.R. Bell: study of dielectric breakdown, generation of high voltage pulses.

The most active person I met seemed to be J.T. Kennair (digital signal processing), who had developed an acoustic sensor to detect air bubbles in the hearts of divers, a device in use by the Admiralty. Kennair had just received a £70,000 grant for additional underwater acoustics: a microprocessor based phased array; 128 transducers; range: 200 m; resolution: 3 cm.

8. University of Oxford

Engineering at Oxford is relatively new. In 1979 there were three professors, a total permanent staff of 40, no separate engineering specialty departments.

In the domain of electronics, the professor is E.G.S. (Ted) Paige, well known for work in SAW and signal processing while at RSRE. Paige arrived at Oxford in 1977 and has been continuing SAW work, in particular surface skimming bulk waves. He collaborates with L. Solymar on work in volume holography.

Solymar has been and continues to be extremely prolific in theoretical work—presently volume holography. (Applications: replace lenses and mirrors by holograms; achieve special optical functions.)

Don Walsh: work on Scanning Optical Microscope. J.E. Allen: basic studies of plasmas (wave propagation; sheaths; optically pumped discharges—possible applications in isotope separation; current multiplication).

I.M. Mason: underground surveying with sonic waves—see *ESN* 34-4:208 (1980).

9. University of Sheffield

Work in Electronic and Electrical Engineering at Sheffield was described in *ESN* 34-8:377 (1980). Outstanding is the research work of the Antenna, Propagation and Digital Image Processing Group, headed by Dr. A.P. Anderson, which combines the traditional aspects of antennas and propagation with an unusual emphasis on complex field data which grew out of holography.

10. University of York

Electronics at York, headed by Prof. G.G. Bloodworth, is very new (1979). A report on this department, as well as on the closely associated Surface Microscopy Group is given in *ESN* 34-3:153 (1980).

B. WALES

Cardiff, the capital and largest city, which lies at almost the southernmost part of Wales, has two separate educational institutions engaged in electronics-oriented research. Located across the street from each other are University College, Cardiff, and UWIST. Another institution, University College of Swansea, lies 40 miles to the west. The fourth, University College of North Wales is in Bangor, 140 miles to the north.

1. University College, Cardiff (UCC)

The outstanding group at UCC is the Wolfson Centre for Magnetics Technology, SRC's Centre of Excellence for applied magnetics research. The director is Prof. J.E. Thompson, who is also Head of the Department of Electrical and Electronic Engineering. Projects extend across the whole spectrum of magnetics, from magnetic recording and thin film technology to permanent magnets, electrical sheet steel, transformers, etc. In addition to the academic staff (Thompson and Drs. A.J. Moses, A.J. Collins, A. Basak, and K.J. Overshot), there are over 50 graduate students in the Centre.

Other work:

(a) Prof. M. Healey—industrial applications of microprocessors.
(b) Dr. D.H. Horrocks and A.B. Wilkinson—digital and analog circuitry.
(c) Dr. K.J. Overshot—novel electrical machines, control and improvement of small commutator machines.
(d) Dr. V. Cook—a power system protection project.

2. University of Wales Institute of Science and Technology (UWIST)

Prof. D.J. Harris heads an academic staff of 28 that offers separate academic programs in Applied Physics, Electronics, Electronic Engineering, and Power Engineering. Accordingly, there is a variety of research:

(a) Prof. Harris: Waveguides for the 100-1,000 GHz range; open-resonator technique for 100 GHz particle-scattering cross-section measurement.

(b) Dr. H. Thomas: Trap profiling in GaAsP by technique of deep level transient spectroscopy; device modeling and work toward improvement in efficiency of GaAsP p+-n cold cathodes activated by low work function surface coating—efficiency up to 2.5% obtained.

(c) Dr. J.E. Aubrey: Resistivity, nonlinear transport, and diffusion size effect studies of bismith and germanium at liquid helium temperatures.

(d) Prof. J.E. Parrott: Double solar cells; in joint effort with Plessey Co., study of behavior of solar cells at high temperatures; graded junction GaAs/GaAlAs solar cells.

(e) Dr. B. Thomas: Characteristics of semiconductor lasers. Polymers for radiation dosimetry.

(f) Dr. G. Morgan: Studies to increase dynamic range of MESFETs at X-band (possibly by mismatching to input and output); use of $Ba_2Ti_9O_{20}$ (ϵ_r=39) to construct high-Q resonators from 2 to 6 GHz; pulse compression using digital filtering.

(g) G. Pearce, Dr. R.W. Bunce: Develop materials for gamma and X-ray detection and application of detectors. (Example: pill 27 mm x 10 mm diameter containing mercuric iodide crystal, amplifier, frequency modulated 106 MHz transmitter, and battery, for localizing bleeding sites in a gastrointestinal tract.)

(h) Dr. D.M. Rowe: Thermoelectric power generation; fine-grained silicon-germanium alloys as thermoelectric materials; ferroelectric materials; phonon scattering.

3. University College of Swansea

The academic staff of 15 in Electrical and Electronic Engineering is headed by Prof. H.A. Barker, the only professor.

Most interesting from a physiological point of view is the work on electrical stimulation of bone healing, by Dr. J. Watson. (See *Proc. IEEE*, Vol. 67, Sept. 1979; pp.1339-1352.)

Principal research efforts: Instrumentation and Communications.

Instrumentation: W.A. Evans, who received equipment of value £75,000 in 1979-80, has designed high precision loss-tangent bridges, inductance measurement bridges with high dc current, a spectrum analyzer, harmonic distortion measurement equipment, signal sources—generally in collaboration with industry.

Communications: Dr. R.C.V. Marcario and Dr. V.J. Phillips. According to Marcario, the U.S. Navy's "Sanguine" and "Omega" systems are based on work he performed at King's College of the University of London in the 1950s. Marcario has ten graduate students, mostly from overseas. Considerable work in mobile radio, digital tuning. Phillips works with speech communication systems (scrambling, etc.); digitizing speech; has patented system to enhance consonants, for hard-of-hearing.

4. University College of North Wales

UCNW, in Bangor, lies in an area whose people formerly subsisted by mining slate, now Bangor is industrially depressed. Yet, with an academic staff of 23, there is a lot of research activity in the School of Electronic Engineering Science (Head, Prof. R.J.A. Paul—linear digital stepping devices; linear reluctance actuators; control of nonlinear multivariable systems):

Electrical Material Science:

1) Charge transport and dielectric processes in insulating and semi-insulating solids. Examples: metal-dielectric contact phenomena (Prof. T.J. Lewis, Dr. R. Toomer); electron-beam-induced conductivity in silicon dioxide thin films (Dr. D.M. Taylor).

2) Electron spectroscopy. Example: electron spectroscopy of organic polymers (Dr. D.K. Das-Gupta).

Electronic Devices and Circuits:

1) Scanning electron microscope study of semiconductor devices. Example: development of a sampling mode attachment for the adaption of standard SEMs for the study of very fast logic circuits (Dr. A. Gopinath—now at MIT Lincoln Labs—Prof. P. Secker, Dr. K.A. Hughes).

2) Microwave integrated circuits and devices. Examples: computer-aided design of microwave integrated circuits (Dr. A. Gopinath, B. Easter, Prof. I.M. Stephenson); edge-coupled microstrip sections as impedance transformers (Dr. B. Easter, Prof. I.M. Stephenson).

3) Microprocessor-controlled peripherals; circuit engineering (A.R. Owens).

Systems and Control Engineering:

1) Control of electromagnetic devices. Example: new magnetic levitation systems (Dr. P.J. Fleming, Prof. R.J.A. Paul).

2) Radio-navigation systems (Dr. J.D. Last).

3) Control system design. Example: controller designs for a gas turbine engine (Dr. P.J. Fleming, Prof. R.J.A. Paul).

4) Marine technology. Example: measurement of subsurface vertical velocities in the sea (Dr. M.H. Lorenz).

5) Application of discrete mathematics (P. Everett).

Laboratory of the National Foundation for Cancer Research receives some US support. (Dr. R. Pethig, Prof. J.J. Lewis). The specific science supported at Bangor has the main objective of investigating the nature of healthy and cancerous cells at the submolecular electronic level. In addition to Pethig and Lewis, there are presently five research students, a cytologist, two research fellows, and a technician. Present research; electronic and dielectric properties of cells, artificial lipid membranes, and proteins and enzymes that have undergone charge transfer reactions.

Industrial Development Bangor (UCNW) Ltd. (Prof. P.E. Secker). This unit, with a staff of 18, is a financially self-supporting engineering company concerned with the design and manufacturing of equipment complementary to but based on the research interests of UCNW. Present products are: radio-location equipment, electrostatic measurement and control instruments, signal processors for scanning electron microscopes, electromedical equipment for cancer therapy, and instrumentation for steel rolling mills.

C. SCOTLAND

1. University of Dundee

Work of interest to the electrical/electronics field performed in physics (Prof. J.J. Standley, Chairman) and in electrical and electronic engineering (EEE—Prof. Brian Makin, Chairman); most widely known individual is Prof. Walter E. Spear, who originated glow discharge deposition of amorphous silicon. At the time of my visit (Dec. 1979) Spear and co-worker Dr. P.G. LeComber worked on amorphous photovoltaic cells, high current pn junctions, and a thin-film-transistor display panel.

Standley has small group performing microwave work, in particular, trying to unravel causes of microwave losses in ferrites, specifically, polycrystalline garnets. (This is an old problem that, according to Standley, is still not solved.) Group is also looking at thin films.

Prof. A.P. Cracknell: recently calculated mode spacing of magnetostatic modes in thin films; group theory in solids; remote sensing of the sea from satellites—to look for pollution of the sea.

Brian Makin: electrostatic deposition of epoxy powder (to apply paint to surfaces—objective is to save on the use of solvents; was constructing a 10-ft. chamber with traveling electric field that moves the dust particles of the powder. (Not possible with conducting powders but functions with powders of resistivity of 10^7 ohm-m and higher.) EEE also collects weather information from satellite, principally for archival purposes, distribution to local industries.

J.T. Edmond, also in EEE, has worked with Arsenic Trisulfide and Triselenide glasses; had developed a thermometer for 400°C range (100 ohms to 10^6 ohms for $\Delta T=250°C$); was trying to understand optical absorption curve of $As_{48}\ S_{71}\ Te_1$ at time of my visit.

2. University of Edinburgh

Edinburgh is now a center of the electronics industry, as well as of heavy engineering and ship repair. There are two universities in Edinburgh; the other is Heriot-Watt (see below).

Chairman of Electrical Engineering at Edinburgh since 1977 is the very enterprising Prof. Jeffrey H. Collins. The department specializes in signal processing and in semiconductor devices and integrated circuits; thanks to Collins, it is now offering an American-type MSc, with theme, "Design and Manufacturing of Electronics Systems."

Signal processing work has dealt with SAW, CCDs, and digital circuits and has been carried out by Collins, Dr. P.M. Grant, Dr. J.M. Hannah, and Dr. M.A. Jack. Examples are work of Jack on SAW Fourier transformers, and cepstrum analyzers. (See *IEEE Trans. on Aerospace and Electronic Systems*, Vol. AES-13, Nov. 1977, pp. 610-618.)

A Central Microcircuit Processing Facility for silicon MOS, under direction of Dr. J.M. Robertson, was under construction at the time of my visit. (See Section II-4a, above.)

Closely associated with the department: the Wolfson Microelectronics Institute of the Univ. Of Edinburgh. (See section II-4b-i, above.)

Dr. A.E. Owen and his group were carrying out studies of the electronic properties and device applications of amorphous materials Work at the time of my visit: study of materials based on As_2Se_3, $As_2 Te_3$, a Ovonic Switch for a high-radiation environment, and Chem FETs.

3. University of Glasgow

The James Watt Professor of Electrical Engineering, Dr. John Lamb, has the principal and relatively large effort in electronics and materials engineering, with heavy concentration in integrated optics (IO) supported by SRC. There are numerous projects in such subjects as high resolution photolithography for optical waveguide devices, holographic diffraction gratings, integration of planar optical components, fast-switching integrated-optical light beam deflection devices, digital logic devices based on gyrotropic waveguides at optical wavelengths, etc. Group leaders for this work are Dr. P.J.R. Laybourn and Dr. C. Wilkinson.

Related to the optical thin film work is a capital-equipment-intensive effort of molecular beam epitaxy (MBE) for III-V and II-VI compounds for solar cell investigations, lasers for IO, and light emitting diodes.

In a separate field of materials research, others in Lamb's group use electrical measuring techniques to determine the viscoelastic and ultrasonic behavior of liquids and melts.

There is other work in systems engineering, control and simulation, control of power systems, applications of control and pattern recognition to biological and man-machine systems, and hydraulic machines. Active in a number of such efforts is Dr. D.J. Murray-Smith, who, during my visit, discussed monitoring of blood flow of postoperative patients by non-invasive techniques and experimental investigation and modeling of mammalian muscle spindle.

In summary, Lamb has been successful in building a group that is well endowed with the necessary equipment for a range of I.O. investigations, and with several enthusiastic younger staff members capable of keeping the group in the forefront (see *ESN* 34-2:70 (1980).

4. Heriot-Watt University

H-W is located in Edinburgh. The best-known effort of electrical and electronic engineering at H-W is construction and operation of ANGUS craft, which are remotely controlled unmanned submersibles for continental shelf sea-bed survey applications and are the focus of hands-on research projects in computer control and robotics. (Principals: Dr. Robin Holmes and Dr. Robin Dunbar).

Prof. Fred Heath and Dr. Patrick Foulk are engaged in computer technology, such as application of directed graphs to design of computer hardware. Other work is on other computer-aided design of digital hardware (Dr. G.T. Russell); machine-readable texts; data base machines based on content rather than index; adaptive systems (with some application to ANGUS).

Recent electromagnetics work, due to Dr. A.J. Sangster, covers radiation from slots in waveguides, slot coupling (using Sangster's 1965 variational method), analysis of the traveling wave gyrotron, and scanning antennas.

Other research covers such diverse topics as noise and vibration produced by small electrical machines, electrical breakdown in solids and liquid helium, and signal processing (Prof. G.R. Nicoll).

A number of individuals in this department appear to have oriented their research to practical problems, so that SRC funds are supplemented by industrial funds.

5. University of Strathclyde

Strathclyde is located in Glasgow.

An impressive array of research projects is in progress in the School of Electrical and Electronic Engineering at Strathclyde. There are two departments. One of these, Electrical Engineering, headed by Prof. D.J. Tedford, with an academic staff of 20, performs research in the performance of small isolated or semisolated power systems; optimal system operation, planning and control; modeling of machines; machine control; circuit interruption; high voltage engineering; fundamental and design studies in solids, gases, liquids, and vacuum; amorphous semiconductors; instrumentation and measurement. There is considerable support from both government agencies, foundations, and industry. Representative projects of ongoing research are: (1) Development of prototype SF_6 puffer circuit breaker; (2) Microprocessor machine control; (3) Corona and breakdown in nonuniform field gaps; (4) Breakdown between coated electrodes in transformer oil; (5) Mechanism of water treeing; (6) Aging and phase transitions in amorphous semiconductors and insulators; (7) Conduction processes in polymers.

The Department of Electronic Science and Telecommunications, headed by Prof. A.M. Rosie, has an academic staff of 11. The research activities fall in the areas of electronics, telecommunications, and control, again with sponsorship by government and industry. A principal effort involves ultrasonic inspection techniques for offshore structures, for the Department is a major partner in the Strathclyde University Centre for Marine Technology, whose mission is research on maintenance of offshore structures.

Present work involves: (1) design of a comprehensive instrumentation system based on optimization studies of probe configurations which require minimal diver intervention; (2) implementation of scanning arrays to facilitate inspection of inaccessible regions; and (3) the study of signal processing techniques for data acquisition and defect characterization. Some of the research project titles associated with this work and others are: (1) Underwater navigation; (2) Acoustic imaging and holographic techniques; (3) Nuclear electronics; (4) Multidimensional filtering; (5) Digital image reconstruction; (6) Telephone traffic theory; (7) Bandwidth compression; (8) Multilevel control systems using microprocessors.

An individual who is responsible for or involved in many of these projects is Dr. T.S. Durrani; I was quite impressed with his knowledge and range of activities.

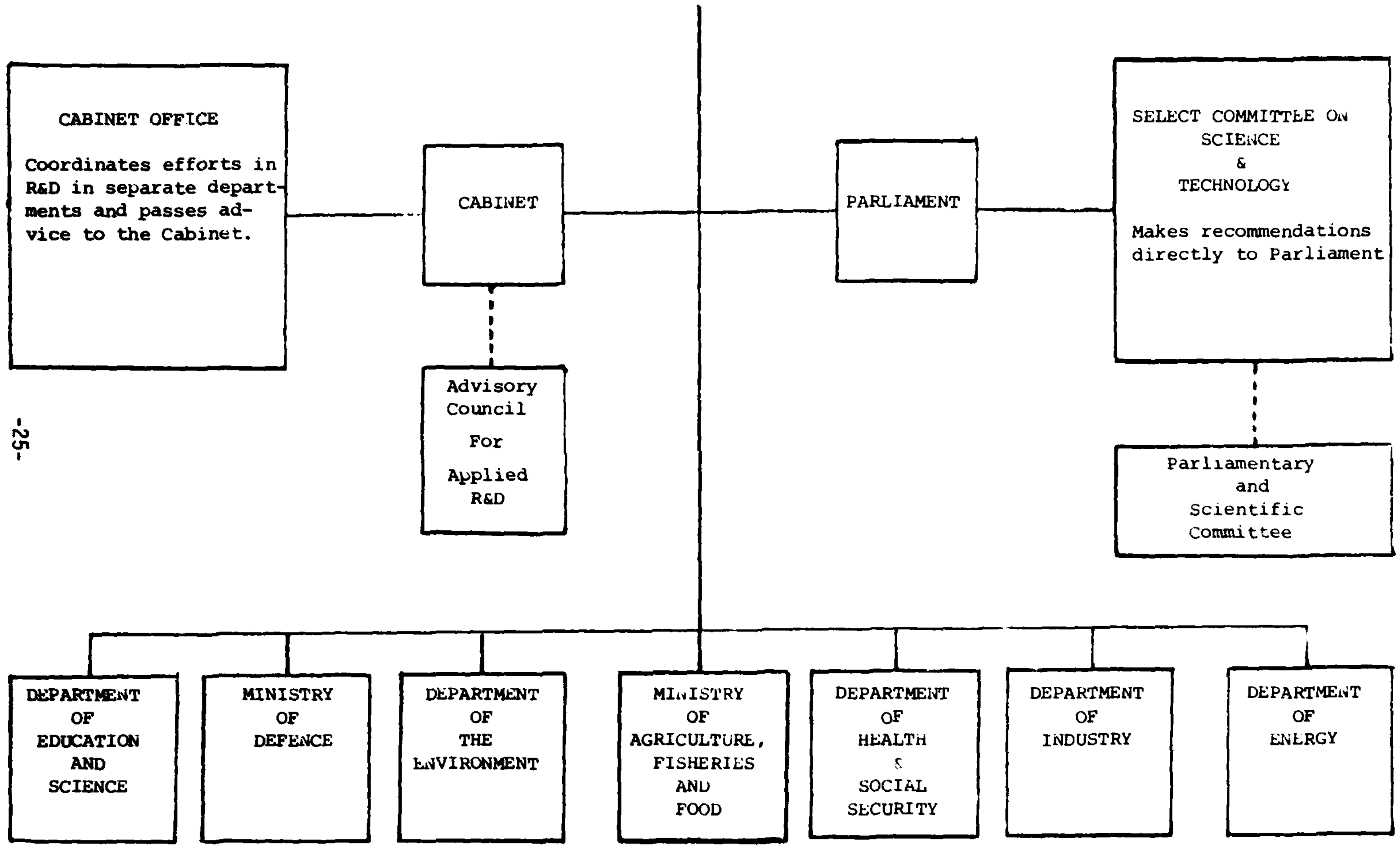

CABINET OFFICE
Coordinates efforts in R&D in separate departments and passes advice to the Cabinet.
CABINET
Advisory Council For Applied R&D
PARLIAMENT
SELECT COMMITTEE ON SCIENCE & TECHNOLOGY
Makes recommendations directly to Parliament
Parliamentary and Scientific Committee
DEPARTMENT OF EDUCATION AND SCIENCE
MINISTRY OF DEFENCE
DEPARTMENT OF THE ENVIRONMENT
MINISTRY OF AGRICULTURE, FISHERIES AND FOOD
DEPARTMENT OF HEALTH & SOCIAL SECURITY
DEPARTMENT OF INDUSTRY
DEPARTMENT OF ENERGY

Fig. 1(a)

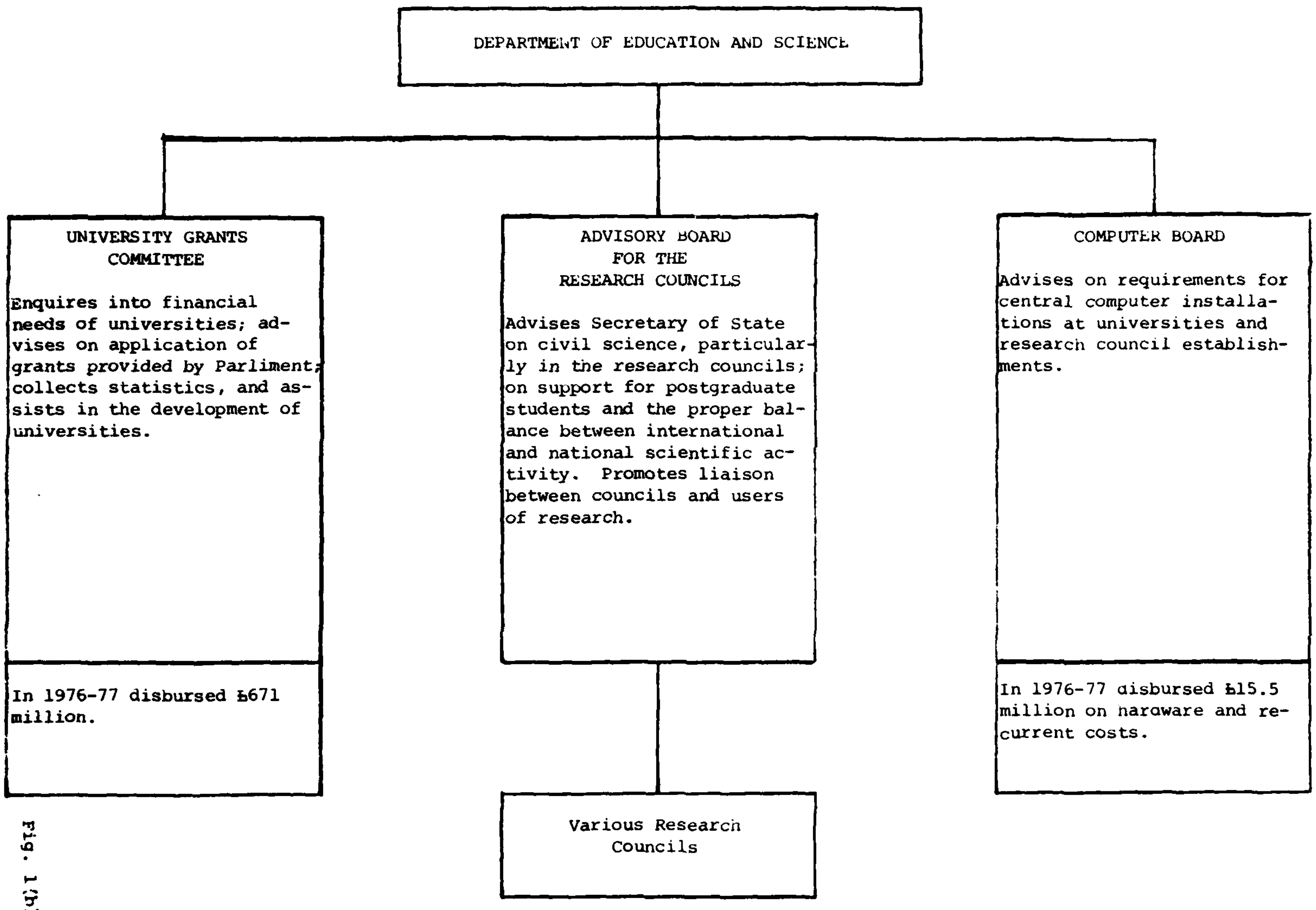
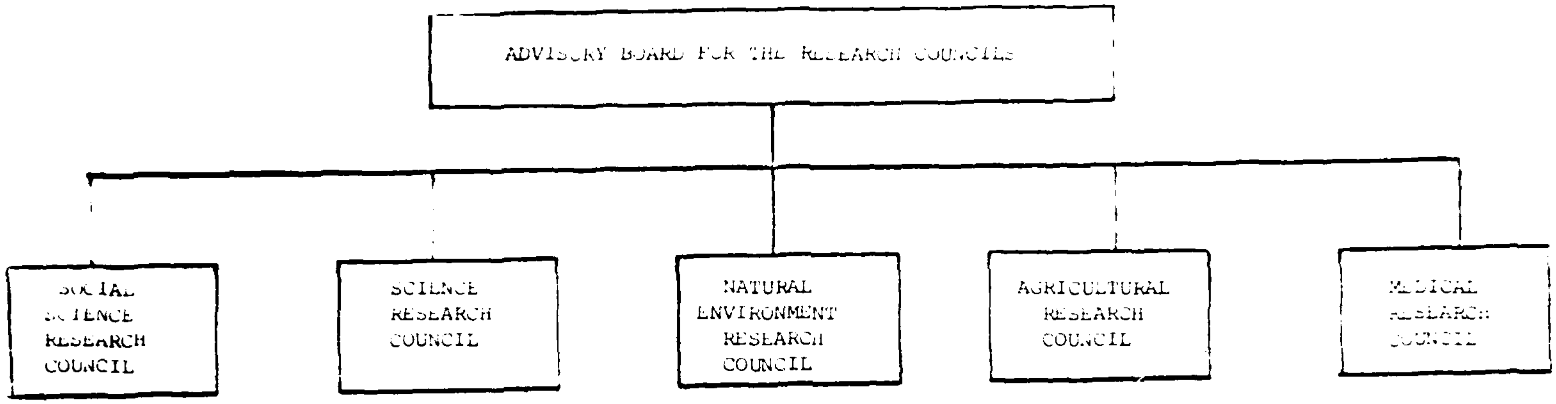

DEPARTMENT OF EDUCATION AND SCIENCE
UNIVERSITY GRANTS COMMITTEE
Enquires into financial needs of universities; advises on application of grants provided by Parliment; collects statistics, and assists in the development of universities.
In 1976-77 disbursed £671 million.
ADVISORY BOARD FOR THE RESEARCH COUNCILS
Advises Secretary of State on civil science, particularly in the research councils; on support for postgraduate students and the proper balance between international and national scientific activity. Promotes liaison between councils and users of research.
Various Research Councils
COMPUTER BOARD
Advises on requirements for central computer installations at universities and research council establishments.
In 1976-77 disbursed £15.5 million on hardware and recurrent costs.

Fig. 1(b)



Operates or supports:

Appleton Laboratory, Daresburg Laboratory, Royal Greenwich Observatory, Royal Observatory Edinburgh, Rutherford Laboratory. Contributes to CERN, ESA, NATO, etc. Has four (4) boards: Astronomy, Space and Radio; Engineering; Nuclear Physics; Science.

1976-77 Expenditure: £127.7 Million

+ A number of independent foundations.

+ Industrial Research. 1976-77 total expenditure by British industry on R&D was £1,345 million

Fig. 1(c)

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